## METHOD AND APPARATUS FOR IMPROVING THE DYNAMIC RANGE OF LASER DETECTED ULTRASONIC IN ATTENUATIVE MATERIALS

5  ## TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to a field of optical information processing and more particularly to a method and system for detecting ultrasonic displacements in a material under test utilizing a time-varying output pulse of a laser beam.

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BACKGROUND OF THE INVENTION

In recent years, the use of advanced composite structures has experienced tremendous growth in the aerospace, automotive, and many other commercial industries.  While composite materials offer significant improvements

5      in performance, they require strict quality control procedures in the manufacturing processes.  Specifically, non-destructive evaluation ("NDE") methods are required to assess the structural integrity of composite structures, for example, to detect inclusions, de-laminations and porosities.  Conventional NDE methods, however, are very slow, labor-intensive, and costly.  As a result, testing

10     procedures adversely increase the manufacturing costs associated with composite structures.

Various systems and techniques have been proposed to assess the structural integrity of composite structures.  One method to generate and detect ultrasound using lasers discloses the use of a first modulated, pulsed laser beam

15     for generating ultrasound on a work piece and a second pulsed laser beam for detecting the ultrasound.  Phase modulated light from the second laser beam is then demodulated to obtain a signal representative of the ultrasonic motion at the surface of the work piece.

Another method to generate and detect ultrasound using lasers discloses

20     the use of a laser to detect deformations of a oscillatory or transient nature on a material under test surface.  The deformations on the material under test surface can be produced by an ultrasound wave or other excitation.  Light from the laser is scattered by the deformations, some of which light is collected by collecting optics and transmitted via a fiber optic to a beam splitter which deflects a small

25     portion of the collected light to a reference detector and delivers the remaining portion of the light to a confocal Fabry-Perot interferometer, which generates an output signal indicative of the deformations on the material under test surface.  The reference detector measures the intensity of the scattered laser light at the input of the interferometer to generate a reference signal.  A stabilization detector

30     measures the intensity of the scattered laser light at the output of the interferometer to generate a prestabilization signal.  The ratio of the reference

signal to the prestabilization signal is used to generate a final stabilization signal which drives a piezoelectric pusher inside the interferometer to adjust its resonant frequency.

5    The advanced composite structures often attenuate ultrasound within the composite materials. It would be desirable to have a system capable of expanding the dynamic range of ultrasound detection in an attenuative material such as advanced composites.

The above-referenced methods attempt to reduce the noise associated with the detection schemes. However, the methods disclosed do not explore
10   expanding and improving the dynamic range of ultrasound detection in attenuative materials.

Therefore, there is a need has arisen for a method and system of ultrasonic laser detection that overcomes the disadvantages and deficiencies of the prior art. Namely, such a system should be able to extend the dynamic
15   range of ultrasound detection in an attenuative material.

## SUMMARY OF THE INVENTION

The present invention provides a method and system for detecting ultrasonic displacements at a remote target under test utilizing a laser beam that substantially eliminates or reduces disadvantages and problems associated with previously developed ultrasonic detection systems.

More specifically, the present invention provides a system for detecting ultrasonic displacements at a remote target with a laser beam having a time dependent pulse profile. The system and method for improving the dynamic range of laser detected ultrasonic in attenuative materials includes a seed laser light source. This laser source produces a laser which is modulated by an assembly placed in the laser beam's path. The modulated laser has a time-dependent pulse profile. Ultrasonics at the remote target further modulate, reflect and/or scatter the laser beam to produce phase-modulated light. Optics collect this phase modulated light. An interferometer coupled to the collection optics demodulates the phase-modulated light and provide an output signal representative of the ultrasonics at the remote target.

A processor may be utilized to process output signal of the interferometer to obtain data representative of the ultrasonics.

Another embodiment of the present invention involves matching the time-dependent pulse profile of the detection laser beam to the attenuative properties of the remote target. Alternatively, the time-dependent pulse profile may be varied to increase the signal strength of the detected ultrasonics.

The present invention provides an important technical advantage by extending the dynamic range of a Laser UT system. Previous systems would synchronize the generation of the ultrasonic event with the peak of the detection laser to maximize signal-noise-ratio without regard for potential dynamic range improvements based on exploiting non-uniform illumination profiles, while the present invention provides that the use of time-dependent detection laser illumination profiles can be used to both optimize signal-noise-ratio and extend the dynamic range of the Laser UT systems.

Another technical advantage of the present invention is an extended dynamic range with which to detect ultrasound in the material under test and improved signal-to-noise ratio due to the time-varying pulse profiles of the detection laser.

Yet another technical advantage of the present invention is the ability to use a detection laser with lower output power. This allows the use of smaller collection optics and optical scanners. Additionally, the use of a lower power detection laser reduces the total power applied to the material under test and damage of the material under test.

Stored energy in amplifier can be extracted in an optimum way to match the properties of the material under test.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

FIGURE 1 depicts a known setup for detecting ultrasonic displacements using a detection laser beam;

FIGURE 2 illustrates shows an embodiment of the present invention using a time-dependent output pulse profile to yield an improved signal-to-noise ratio;

FIGURE 3A illustrates a gaussian or lorentzian time-dependent pulse profile;

FIGURE 3B illustrates a linear ramp to a gain clamped time-dependent pulse profile;

FIGURE 3C illustrates an exponential ramp to a gain clamped time-dependent pulse profile; and

FIGURE 4 illustrates a typical plot of frequency dependent material attenuation.

DETAILED DESCRIPTION OF THE INVENTION

        Preferred embodiments of the present invention and its advantages are
understood by referring to FIGUREs 1 through 6 of the drawings, like numerals
being used for like and corresponding parts of the various drawings.

5       FIGURE 1 illustrates a detection system 100 for detecting ultrasonic
displacements 102 at remote target 104. Detection system 100 utilizes a
detection laser source 106 to generate a laser beam 108. Detection laser source
106 may incorporate a multi-pass optical amplifier 110, driven by pump source
drive electronics 109 to generate laser beam 108 with a power $P_0$. Ultrasonic
10   displacements 102 at remote target 104 modulate, scatter and reflect detection
laser beam 108. When detection laser beam 108 interacts with the ultrasonic
waves or displacements 102 present at remote target 104, detection laser beam
108 is reflected or scattered as phase-modulated light 112. Phase-modulated
light 112 is reflected and scattered in all directions as shown by arrows 114.
15   However, some of the phase-modulated light 112 is captured by collection optics
116. Collection optics 116 direct phase-modulated light 112 via fiber optic 118
into interferometer 120. Interferometer 120 demodulates the phase-modulated
light and directs an output into detector 122 which generates an analog signal for
processing.

20       Scattering of the laser beam by the material under test includes all
reactions between laser beam 108 and the material under test where laser beam
108 is redirected without otherwise altering the laser beam; furthermore
scattering a laser beam by the material under test includes all reactions between
the phase modulated light and the material under test with the exception of
25   absorption of the first pulsed laser beam.

        Collection optics 116 has an aperture size of $\phi$ and is spaced a distance
D from remote target 104. The power of the collected, phase-modulated light as
measured at the output of the collector is $P_c$. The power of the collected, phase-
modulated light at the input of the interferometer is substantially $P_c$ since there is
30   very little transmission loss associated with fiber optic 118. Because the loss in

interferometer is minimal, the power of the input signal to the detector ($P_{DET}$) is substantially the same as $P_c$.

The signal-to-noise ratio of detector 122 is directly proportional to the square root of the input power:

$$SNR \propto \sqrt{P_{DET}} \qquad\qquad \text{eqn (1)}$$

The above formulas suggest that the SNR can be improved by increasing $P_o$, or $\phi$, or by decreasing D. Increasing the ratio of $\phi/D$ decreases the depth of field of detection system 100, which is undesirable because a decreased depth of field is less flexible.

Alternatively, $P_o$ can be increased. One approach to increase the output of detection laser 106 is to use a shorter pulse width. The pulse of detection laser beam 108, however, must be of a sufficient width to permit detection of ultrasonic displacements, and therefore, decreasing its pulse duration degrades its ability to detect such displacements. A second approach is to amplify the detection laser using a multiple pass optical amplifier. However, the gain of a conventional optical amplifier is dependent upon the power of the input signal.

Where the $P_{DET}$ is given by eqn (2):

$$P_{DET} = \frac{P_0}{4}\left(\frac{\phi}{D}\right)^2 (1-A)\cdot\cos\sigma\cdot\eta \quad \Leftarrow \text{ for a diffuse surface}$$

Where $P_D$ = incident power

        A = absorption

        $\sigma$ = incident angle

        $\eta$ = efficiency (mirror losses, fiber losses, etc.)

FIGURE 2 illustrates a setup for generating and detecting ultrasonic displacements using a detection laser beam similar to that of FIGURE 1. Detection system 200 utilizes a detection laser 130 to detect ultrasonic displacements 102 on a remote target 104. Detection laser 130 may incorporate an electro optic phase modulator 132 to modulate the laser based on time varying drive voltage. Optical isolator 134 and beam dump 136 to prevent optical feedback into modulator 132. Optical amplifier 138 amplifies the laser beam to produce laser beam 140 with a power $P_{(t)}$. This laser beam 140 can have a time-

dependent pulse profile $P_{(t)}$, this pulse profile can be optimized as to improve the signal strength. This time-dependent pulse profile can be optimized to substantially match the attenuation characteristics of remote target 104. Alternatively, a time-dependent pulse profile can be used which does not match the attenuation characteristics of remote target 104 but does provide sufficient variation in the intensity of the pulse profile to alter the dynamic range of the ultrasonic detection process. FIGUREs 3A through 3C illustrate potential pulse shapes, including a gaussian or lorentzian pulse shape as shown in FIGURE 3A; a linear ramp/gain clamping pulse shape as shown in FIGURE 3B; and an exponential pulse shape as shown in FIGURE 3C. The present invention need not be limited to the time-dependent pulse profiles described in FIGUREs 3A through 3C. Rather, advantageous pulse profiles may be taken such that the signal strength actually increases during the duration of the detection pulse.

The present invention provides a system for detecting ultrasonic displacements at a remote target. The ultrasonic displacements 102 at remote target 104 modulate, scatter and reflect detection laser beam 140, represented by arrows 142 directed away from the remote target 104. When detection laser beam 140 interacts with ultrasonic waves 102, detection laser beam 140 is reflected and/or scattered as phase-modulated light 142. This phase-modulated light contains information representative of the ultrasonic displacements 112 at remote target 104.

Ultrasonic material displacements 102 are a function of both time and attenuation of the material from which remote target 104 is constructed. This function is shown below in Equation 1.

$$U_{(t)} = U_0 e^{-\alpha_{(f)} t} \qquad \text{(EQN 1)}$$

Where $\alpha_{(f)}$ is the frequency dependent material attenuation as shown in FIGURE 4. The measured signal at the detector is given by Equation 2, as follows:

$$S_{(t)} = K \cdot P_{(t)} \cdot U_{(t)} \qquad \text{(EQN 2)}$$

Where K is a constant, $P_{(t)}$ is the detection laser power and $U_{(t)}$ is the ultrasonic displacements defined in Equation 1. Over a small frequency range ($\Delta f$), the

frequency-dependent material attenuation as shown in FIGURE 4 can be
approximated by a constant:

$\alpha_{(f)} \approx \alpha_0$

Further, the time–dependent pulse profile $P_{(t)}$ can be adjusted such that the pulse

5    profile of the laser 140 substantially matches the attenuation characteristics of
the material under test, as shown by the below approximation: $P_{(t)} \approx e^{+\alpha_0 t}$. These
approximations associated with the exponential pulse profile of FIGURE 3C, yield
a measured signal described by Equation 3 below:

$S_{(t)} = K \cdot U_0 \cdot e^{+\alpha_0 t} \cdot e^{-\alpha_0 t} = K \cdot U_0$          (EQN 3)

10   Here, the pulse profile, $P_{(t)}$, has been made to exactly match the attenuation loss,
yielding a constant measured signal strength over time.

      Similarly, the pulse profiles provided in FIGUREs 3A and 3B allow for an
improved signal strength response utilizing a different $P_{(t)}$ function.

      More specifically, the present invention provides a system for detecting

15   ultrasonic displacements at a remote target with a laser beam having a time
dependent pulse profile.  The system and method for improving the dynamic
range of laser detected ultrasonic in attenuative materials includes a seed laser
light source.  This laser source produces a laser which is modulated by an
assembly placed in the laser beam's path.  The modulated laser has a time-

20   dependent pulse profile.  Ultrasonics at the remote target further modulate,
reflect and/or scatter the laser beam to produce phase-modulated light.  Optics
collect this phase modulated light.  An interferometer is coupled to the collection
optics to demodulate the phase-modulated light and provide an output signal
representative of the ultrasonics at the remote target.

25      A processor may be utilized to process the one output signal of the
interferometer to obtain data representative of the ultrasonics.

      Another embodiment of the present invention involves matching the time-
dependent pulse profile of the detection laser beam to the attenuative properties
of the remote target.  Alternatively, the time-dependent pulse profile may be

30   varied to increase the signal strength of the detected ultrasonics.

The present invention provides an important technical advantage by extending the dynamic range of a Laser UT system. Previous systems would synchronize the generation of the ultrasonic event with the peak of the detection laser to maximize signal-noise-ratio without regard for potential dynamic range improvements based on exploiting non-uniform illumination profiles, while the present invention provides that the use of time-dependent detection laser illumination profiles can be used to both optimize signal-noise-ratio and extend the dynamic range of the Laser UT systems.

Another technical advantage of the present invention is an extended dynamic range of the system to detect ultrasound in the material under test and improved signal-to-noise ratio for the system due to the time-varying pulse profiles of the detection laser. The time-varying signal can be matched to the attenuative properties of the material, thus optimizing the signal-to-noise ratio of the output signal provided by the detection laser.

Yet another technical advantage of the present invention is the ability to use a detection laser with lower output power allowing the use of smaller collection optics and optical scanners. Additionally, the use of a lower power detection laser reduces the total power applied to the material under test and damage of the material under test. This reduced power requirement is due to the improved signal-to-noise ratio and dynamic range achieved by the application of the time-varying laser pulse.

Although the present invention has been particularly shown and described in detail, it should be understood that various changes, substitutions and alterations can be made hereto without departing from the spirit and scope of the invention as defined in the appended claims.